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Switched Reluctance Motor Drives

Switched reluctance machines (SRMs) have salient stator and rotor poles with concentrated windings on the stator and no winding on the rotor. The stator windings can be wound externally and then slid onto the stator poles. This provides for a very simple manufacturing process, thus the cost of the machine is also low. The SRM has a single rotor construction, essentially made of stacks of iron, and does not carry any coils or magnets. This feature gives it a rugged structure and provides the machine with the advantage that it can be used at high speeds and better withstand high temperatures. The SRM achieves high torque levels at low peak currents by using small air gaps. [Figures 9.1](#) and [9.2](#) show a cross-sectional views of a typical 6/4 SRM with six stator and four rotor poles.

The choice of the number of poles to be used in the SRM is important due to the vibration that is produced. A structure such as 12/8 (12 stator and eight rotor poles) provides lower mechanical vibration compared to the 6/4 structure. SRM machines are well

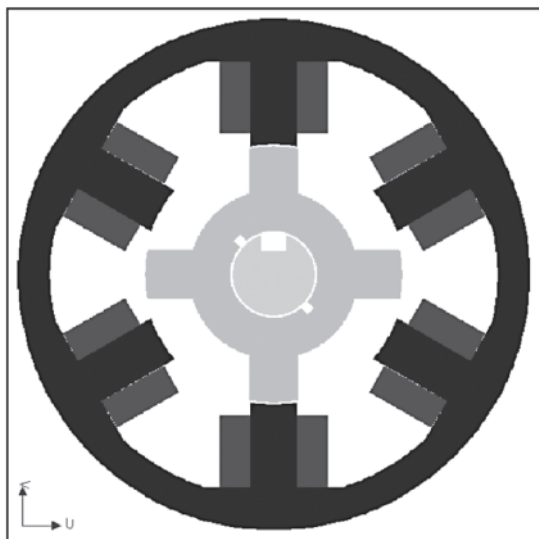


FIGURE 9.1 Cross section of a typical 6/4 SRM with six stator and four rotor poles.

suited for high-speed operations and tend to have higher efficiency at high speeds. They provide constant power over a wide speed range and are highly dynamic with speed. In fact, switched reluctance motor drives are inherently adjustable- or variable-speed drives.

The SRM is a highly reliable machine as it can function even under faulty conditions with reduced performance. One of the reasons for this is that the rotor does not have any excitation source and thus does not generate power into the faulted phase; therefore, no drag torque would be produced under the motoring mode and there are no sparking/fire hazards due to excessive fault currents. In addition, the machine windings are both physically and electromagnetically isolated from one another, reducing the possibility of phase-to-phase faults. The classic SRM drive as a system with converter involves two switches and a winding in series. Thus, even in a case of both switches being turned on at the same time, no

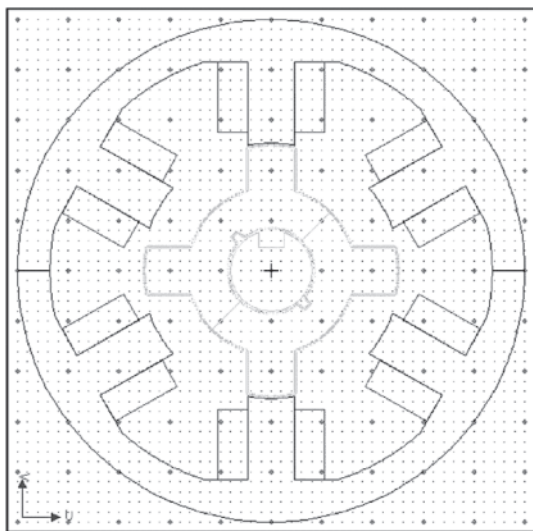


FIGURE 9.2 Cross sectional view of a typical 6/4 SRM with six stator and four rotor poles.

shoot-through faults would occur, unlike the case of AC drives, which lead to shorting of the DC bus.

Switched reluctance machines by a nonsinusoidal voltage waveform, thus resulting in a high torque ripple. This also leads to high noise levels. As per the standards, to have torque ripples of less than 15% in nonsinusoidal excited machines, the number of phases in the SRM has to be increased, which would reflect on the system cost due to the increased number of parts, in this case the switches. A better solution is to use advanced control techniques to reduce the torque ripple and noise. The SRM converters have very high efficiency at low and high speeds. During generation, the efficiency values are remarkably high—above 90%—over a wide speed range.

Electromagnetic torque in the SRM is produced by the tendency of the salient rotor poles to align with the excited stator poles and attain the least reluctance position. The torque developed

depends on the relative position of the phase current with respect to the inductance profile. If the current falls on the negative slope of the inductance profile, then the machine is in the generating mode. The back EMF developed depends on the magnetic parameters of the machine, rotor position, and the geometry of the SRM.

The current waveforms for the motoring mode and the generating modes are mirror images of each other. During generation, initial excitation has to be provided from an external source, it being a single excited structure. The stator coils are turned on around the aligned position and then turned off before unalignment for generating electricity. The turn-on and turn-off angles as well as the current determine the performance of the machine. During the high-speed motoring mode, the peak value of the current depends on the turn-on time. These timings greatly help in designing optimal and protective control. In addition, in SRM, by changing the turn-on and turn-off angles, the system may be optimized to operate under maximum efficiency, minimum torque ripple, or minimum ripple DC link current. The extended constant power/speed ratio capability of the SRM enables less power requirement during the motoring mode.

The SRM can be current controlled for both motoring and generating modes of operation. During motoring the current is controlled by adjusting the firing angles and applying the current during the magnetization period. If during the current control there is overlapping of the phase currents, it leads to an increase in the maximum torque level. During the generation mode of operation, the torque must be fed to the machine when the inductance level is reducing, i.e., when the rotor is moving from the aligned position to the unaligned position.

9.1 HISTORY OF SWITCHED RELUCTANCE MACHINE

The guiding principle behind the SRM drive is that when a magnetically salient rotor is subject to the flow of flux in the magnetic circuit, it tends to move toward the position of minimum reluctance. This phenomenon has been known ever

since the first experiments on electromagnetism. In the first half of the 19th century, scientists all over the world were experimenting with this effect to produce continuous electrical motion. A breakthrough came from W. H. Taylor in 1838, who obtained a patent for an electromagnetic engine in the United States. This machine was composed of a wooden wheel on the surface, on which was mounted seven pieces of soft iron equally spaced around the periphery. The wheel rotated freely in the framework in which four electromagnets were mounted. These magnets were connected to a battery through a mechanical switching arrangement on the shaft of the wheel such that excitation of an electromagnet would attract the nearest piece of soft iron, turning the wheel and energizing the next electromagnet in the sequence to continue the motion. However, the torque pulsations were the main drawback of this machine compared to DC and AC machines.

Improvement was noticed with the introduction of electronic parts that replaced the mechanical arrangements. The trend moved toward reducing the mechanical arrangements and parts while increasing the electronic parts. Improved magnetic material and advances in machine design have brought the SRM into the variable-speed drive market. Presently demand for SRMs is increasing as they offer superior performance with lower price. Other than simplicity and low-cost machine manufacturing, the main motivation toward SRM use is the availability of low-cost power electronic switches, control electronic components, integrated circuits (ICs), microcontrollers, microprocessors, and digital signal processors (DSPs).

In the present global scenario, SRM drives are one of the major emerging technologies in the field of adjustable-speed drives. They have many advantages in terms of machine efficiency, power density, torque density, weight, volume, robustness, and operational flexibility. SRM drives are finding applications in general-purpose industrial drives, traction, devices domestic appliances, and office and business equipment. The emerging markets in consumer and industrial products are very cost sensitive as well as demand high reliability and performance, equivalent to DC and induction motor drives.

9.2 FUNDAMENTALS OF OPERATION

Switched reluctance machines are similar to synchronous machines but with significant distinctive features. They are referred to as doubly salient pole machines as their stator and rotor both have salient poles. This configuration proves to be more effective as far as electromagnetic energy conversion is concerned. Another prominent feature is that there is no coil or permanent magnet (PM) on the rotor. Figure 9.3 shows the rotor and stator of a 10-hp 6/4 SRM with six stator and four rotor poles.

The absence of permanent magnets or coils on the rotor means that torque is produced purely by the saliency of the rotor laminations. The torque is produced with respect to the direction of the flux through the rotor, and hence the direction of the flow of the current in the stator phase windings is not important. The need for unipolar phase current in the reluctance motor results in simpler and more reliable power converter circuits.

9.2.1 Torque Equation

Despite the simple operation of SRMs, an accurate analysis of the motor's behavior requires a relatively complex mathematical approach. The instantaneous voltage across the terminals of a single

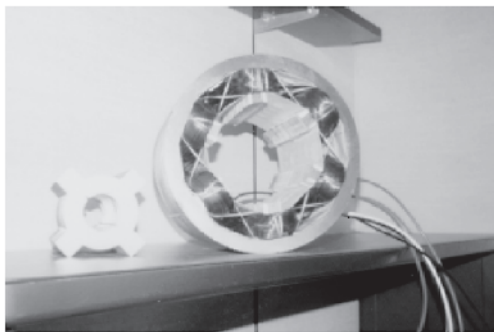


FIGURE 9.3 Rotor and stator of a 10-hp SRM with six stator and four rotor poles.

phase of the motor winding is related to the flux linked in the winding by Faraday's law,

$$v = Ri + \frac{d\phi}{dt}$$

where v is the terminal voltage, i is the phase current, R is the motor resistance, and $d\phi/dt$ is the flux linked by the winding. We can rewrite this equation as follows:

$$v = Ri + \frac{d\phi}{di} \frac{di}{dt} + \frac{d\phi}{d\theta} \frac{d\theta}{dt}$$

where $d\phi/di$ is defined as the instantaneous inductance $L(\theta, i)$ and $d\phi/d\theta$ is defined as the instantaneous back EMF $K_b(\theta, i)$. Figure 9.4 depicts the flux-current characteristic of the machine. The above equation defines the transfer of electrical energy to the magnetic field of the machine. The following equations describe the conversion of the field's energy into mechanical energy. Multiplying each side of Faraday's equation by the electrical current gives an expression for the instantaneous power:

$$vi = Ri^2 + i \frac{d\phi}{dt}$$

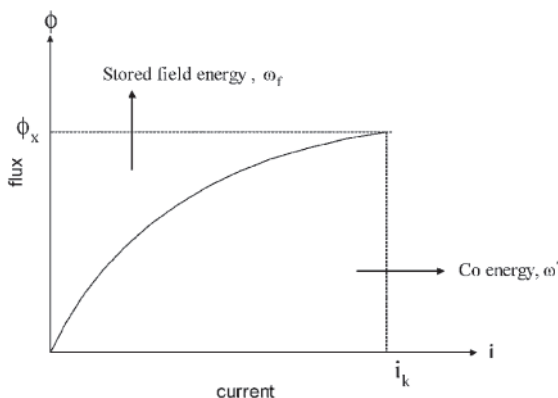


FIGURE 9.4 Flux-current characteristic of an SRM.

The left side of this equation represents the instantaneous electrical-power delivered to the SRM. The first term on the right side represents the resistive losses in the SRM stator winding. If power is to be conserved, then the second term on the right side must represent the sum of the mechanical power output of the machine and any power stored in the magnetic field.

$$i \frac{d\phi}{dt} = \frac{dW_m}{dt} + \frac{dW_f}{dt}$$

$$\frac{dW_m}{dt} = T \frac{d\theta}{dt}$$

Substituting the above torque term, we obtain

$$i \frac{d\phi}{dt} = T \frac{d\theta}{dt} + \frac{dW_f}{dt}$$

By solving the equations, we get

$$T(\theta, \phi) = i(\theta, \phi) \frac{d\phi}{d\theta} - \frac{dW_f(\theta, \phi)}{d\theta}$$

We can simplify to

$$T = - \frac{dW_f}{d\theta}$$

It is better to express torque in terms of the current rather than flux; therefore, torque is expressed in terms of coenergy instead of energy:

$$W_f = \int_0^\phi i(\theta, \phi) d\phi$$

$$W_c = \int_0^i \phi(\theta, i) di$$

W_c is defined as the magnetic field coenergy.

$$W_c + W_f = i\phi$$

Differentiation and substituting in the main torque equation,

$$dW_c + dW_f = \phi di + i d\phi$$

$$T = \frac{id\phi - (\phi di + id\phi - dW_c(\theta, i))}{d\theta}$$

For simplicity, coenergy can be written as

$$dW_c(\theta, i) = \frac{dW_c}{d\theta} d\theta + \frac{dW_c}{di} di$$

$$T = \frac{dW_c}{d\theta}$$

After neglecting the saturation, we can write flux and current as

$$\phi = L(\theta)i$$

Substituting in the coenergy equation,

$$W_c = \frac{1}{2} i^2 L(\theta)$$

The simplified torque equation is obtained as follows:

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

9.2.2 Characteristics of SRMs

The torque-speed characteristic of an SRM depends on the control used in the machine. It is also easily programmable, which makes the SRM attractive. However, there are some limitations due to the physical constraints such as the supply voltage and allowable temperature rise of the motor under increasing load.

As in other motors, torque is limited by the maximum allowed current and speed by the bus voltage. With increasing shaft speed, a current limit region persists until the rotor reaches a speed where the back EMF of the motor is such that, given the DC bus voltage limitation, we can get no more current in the winding, thus no more torque from the motor. At this point, which is called the base speed, we can obtain constant torque operation in which the shaft output power remains constant at its maximum. At still higher speeds, the back EMF increases and the shaft output power begins to drop. The product of the torque and the square of the speed remains constant in this region. The SRM holds an outstanding benefit over other

machines as the ratio between the maximum speed and base speed in this machine is up to 10, which specifies that the SRM has extended speed constant power operation. The torque-speed characteristic is shown in Figure 9.5.

In SRM drives, the phase flux is the sum of the self-flux and the mutual flux. The self-flux is dominated as it goes through mostly iron and two air gaps across the phase poles, while the mutual flux goes to the air gap between the stator poles and interpolar part of the rotor poles. Due to the more effective air gap, there is high reluctance and lower contribution to the phase flux. Hence, the rotor position and related phase currents determine the self-inductance of the phase. Variations in the mutual inductance due to the phase current are practically negligible. There is no variation in self-inductance when the rotor is unaligned, but it decreases when the rotor is near the aligned position. The variation in the mutual inductance is not significant compared to the variations in self-inductance. The inductance characteristic with respect to different rotor positions and different phase current levels is shown in Figure 9.6. Figure 9.7 depicts the flux-current characteristic of

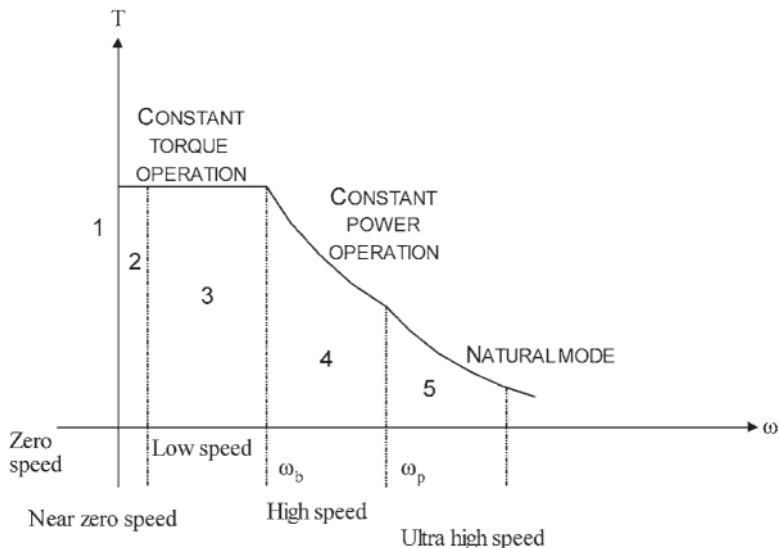


FIGURE 9.5 Torque-speed characteristic of an SRM.

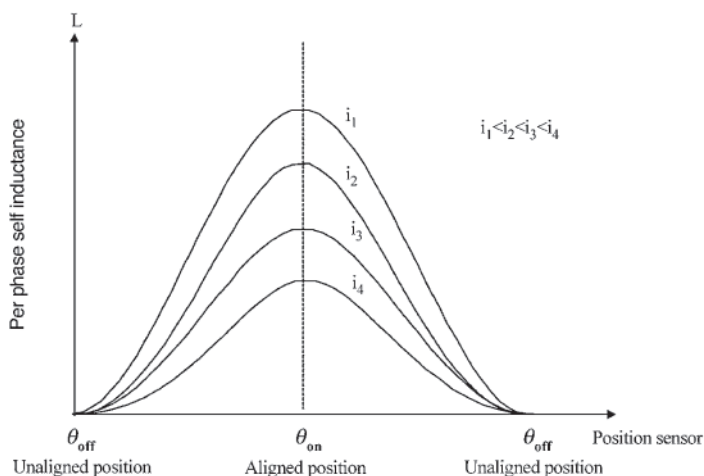


FIGURE 9.6 Self-inductance–rotor position characteristic of an SRM.

an SRM as a function of rotor position. Figures 9.8–9.10 show a flux density map, flux lines, and the wire mesh of a typical 6/4 SRM, respectively.

9.3 MACHINE CONFIGURATIONS

There are several factors that are important in selecting the number of phases and number of poles. The number of phases is determined by the following factors:

- *Starting capability.* When the rotor and stator poles are aligned, the single-phase machine cannot start; therefore, it requires a permanent magnet on the stator at an intermediate position to the stator poles to keep the rotor poles at the unaligned position.
- *Directional capability.* Two-phase machines are capable of only one direction of rotation, whereas three-phase machines are capable of rotation in both directions.
- *Reliability.* A higher number of phases gives higher

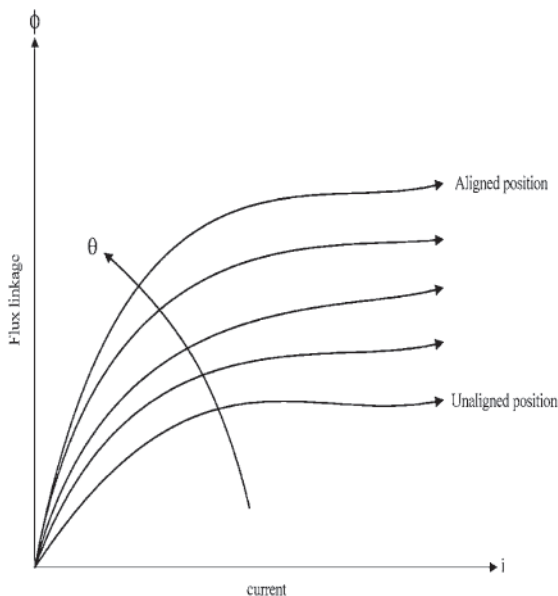


FIGURE 9.7 Flux-current characteristic of an SRM as a function of rotor position.

reliability because a failure of one or more phases will allow the running of the machine with the remaining phases.

- *Cost.* A higher number of phases requires a higher number of converter phase units, their drivers, logic power supplies, and control units, which increases the overall cost.
- *Power density.* A higher number of phases provides higher power density.
- *Efficient high-speed operation.* Efficiency can be increased by reducing the core losses at high speed by decreasing the number of stator phases and lowering the number of phase switching per revolution.

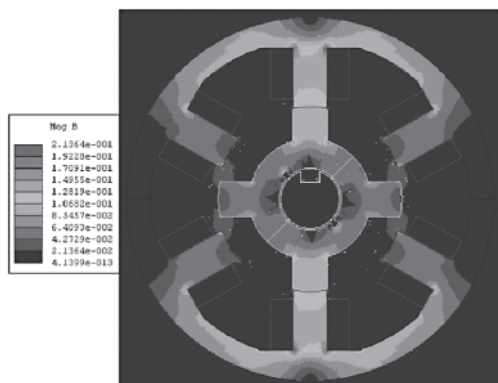


FIGURE 9.8 Flux density map of a typical 6/4 SRM.

In order to select the number of poles for the rotor and stator, the ratio between stator and rotor poles should be a noninteger. Different combinations of stator and rotor poles are given in [Table 9.1](#) for typical SRM drives.

The limiting factors in pole selection are the number of power converter switches and their associated cost of gate drives and logic

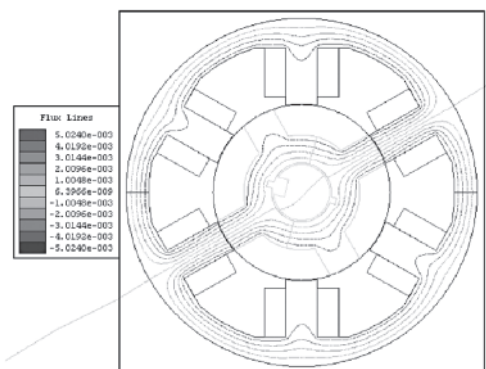


FIGURE 9.9 Flux lines of a typical 6/4 SRM.

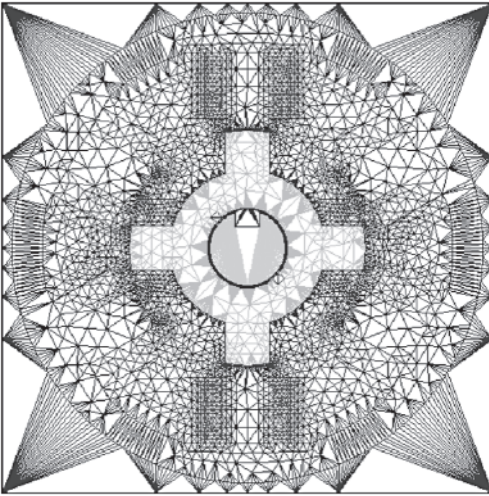


FIGURE 9.10 Wire mesh of a typical 6/4 SRM.

supplies. With the increase in the number of poles, the cost increases due to increased winding insertion cost and terminal cost. Stator frequency is proportional to the number of poles; hence, with the increase in the number of poles, stator frequency increases, which results in higher core losses and considerably greater conduction time to provide rise and fall of the current compared to that of a machine with fewer poles. If the number of rotor poles is less, the copper losses increase and so does the phase conduction overlap. Due to the increased switching frequency, the commutation torque ripple frequency is also increased, thus making its filtering easier. Overlapping phase conductions and their effective control can

TABLE 9.1 Typical Numbers of Stator and Rotor Poles

Stator	6	12	8	12	24
Rotor	4	8	6	10	16

attenuate the commutation torque ripple magnitude, leading to quiet operation. Figures 9.11 and 9.12 show cross-sectional views of a typical 10/6 SRM and a typical 6/4 SRM, respectively.

Switch reluctance machines can offer a wide variety of aspect ratios and salient pole topologies. Single-phase motors are the simplest SRMs with the fewest connections between machine and electronics. The disadvantages lie in very high torque ripple and inability to start at all angular positions. This configuration is attractive for very high-speed applications, but starting problems may preclude their use.

For two-phase motors, the problems of starting compared with the single-phase machines can be overcome by stepping the air gap or providing asymmetry in the rotor poles. This machine may be of interest where the cost of winding connections is important, but again high torque ripple is the disadvantage.

Three-phase motors offer the simplest solution to starting and torque ripple without resorting to high numbers of phases. Hence, 6/4 SRM has been the most popular topology. Alternative three-phase machines with doubled pole numbers can offer a better solution for lower-speed applications. However, torque ripple, especially in the voltage control single-pulse operating mode, is again a drawback.

Four-phase motors are popular for reducing torque ripple further; however, the large number of power devices and connections renders four-phase motors to limited applications. Five-phase



FIGURE 9.11 Half cross section of a typical 10/6 SRM with 10 stator and six rotor poles.

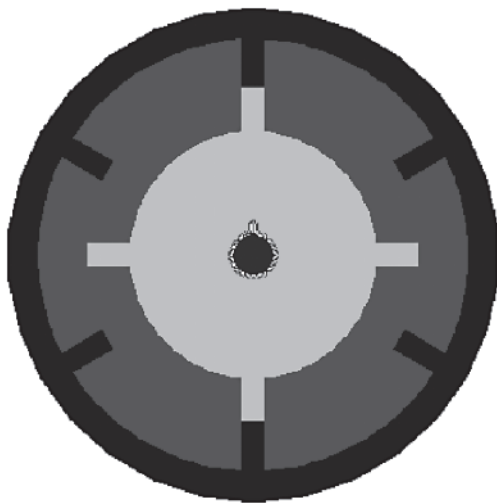


FIGURE 9.12 Cross section of a 6/4 SRM.

and six-phase motors can offer better torque ripple reduction compared with the four-phase and three-phase SRMs.

9.4 DYNAMIC MODELING OF SRMs

Recently, SRMs have been receiving much attention due to their various advantages. First, it has no windings or permanent magnets on the rotor. Thus, it can be mass produced at a fairly low cost compared to the other motor types. Furthermore, the SRM has additional advantages of low inertia, minimal losses on the rotor, and mechanical robustness, which allow it to be driven at high speeds. In addition, the stator windings are concentrated, making it easier to wind compared to the other AC and DC machines. Hence, SRM drive systems have been found to be suitable for home appliances, industrial applications, automotive applications, aircraft starter/generator systems, washing machines, compressors, electric/hybrid electric vehicles, etc.

However, despite its simple appearance, it is more difficult to design due to its nonlinearity. Due to these nonlinearities present in the system, analyzing the complete SRM drive becomes a cumbersome task. Furthermore, simulation of the SRM drive system requires proper modeling of the SRM subsystems. In this regard, various methods of estimating the torque and current of SRM drives have been introduced. In previous research carried out in this area, detailed nonlinear models of variable reluctance motors have been developed. The nonlinear characteristics of flux linkage–current–position are represented by corresponding analytical expressions. In order to obtain such exhaustive results, either through experimental verification or by finite element analysis (FEA) methods, a huge amount of time is required.

In addition, state space models for SRM drives have been developed wherein the phase currents are specified as the state variables (whereas the inductances are specified as parameters). Basically, this method is a more accurate way of representing the phase inductances in the model. Other research work in this area involves simulation of electromechanical energy conversion and the drive control system. Again, as is the case with other modeling methods, this too needs complete information of the inductance–current–position characteristics. Furthermore, this method of modeling does not consider low-speed operation.

Prediction of the dynamic performance of the SRM in various operating regions with accurate results requires a fairly accurate representation of its magnetic characteristics. This means the variation of flux linkage with rotor position and current must be accurately determined. Basically, this section aims at presenting a comprehensive dynamic model for the SRM drive system, which covers both low-speed and high-speed modes of operation. Such a detailed dynamic model takes care of the magnetic nonlinearities in the SRM. Primarily, the variation of phase inductance with rotor position is expressed as a Fourier series wherein the first three components are considered.

The SRM drive system model includes the motor itself, the appropriate power electronic converter, and the related control system. The power electronic converter and the control circuitry are modeled based on their actual configuration. A typical representation

of a classic converter for the SRM drive is shown in Figure. 9.13. This system is an asymmetric driver with a converter with two switches per phase. Therefore, this driver is also named the two-switch-per-phase SRM driver.

In order to understand the working of the above converter, consider only one phase of the SRM (phase A). Turning on transistors T1 and T2 will circulate a current in phase A of the SRM. If the current rises above the commanded value, T1 and T2 are turned off. The energy stored in the motor winding of phase A will keep the current in the same direction (the current decreases). Hence, diodes D1 and D2 will become forward biased, leading to recharging of the source. This will decrease the current, rapidly bringing it below the commanded value.

In order to simulate the dynamic characteristics of the SRM, it is necessary to express the inductance–current–position characteristics of the motor accurately. As was mentioned earlier, for this purpose, the variation of the phase inductance with rotor position is expressed as a Fourier series expansion with only the first three terms being

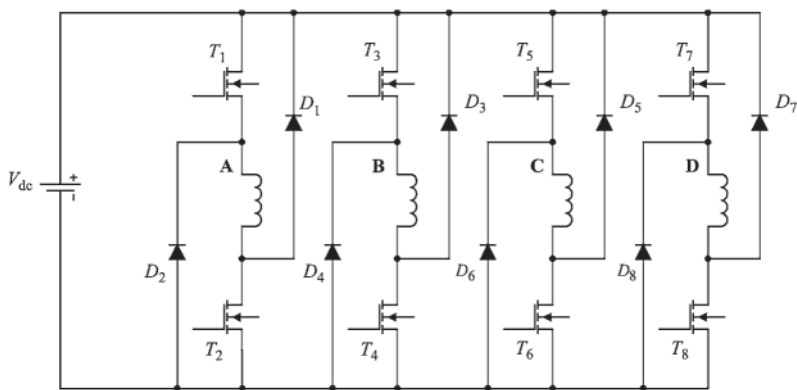


FIGURE 9.13 Layout of a typical classic (two-switch-per-phase) converter for an 8/6 SRM drive system.

considered for analysis. In order to find these coefficients, three distinct points on the inductance–current waveform are used. These points are inductance at the aligned position L_a , unaligned position L_u , and at a position midway between the two L_m . It is worth mentioning here that the mutual inductances of the phases are neglected in this case. The voltage equation for the conducting phase is given as follows:

$$v = Ri + l \frac{di}{dt} + \frac{d\psi}{dt}$$

where v is the voltage applied across the winding, R is the phase winding resistance, l is the phase leakage inductance, $\psi = L(i, \theta)i$ is the flux linkage, and L is the self-inductance of the phase.

As mentioned before, the self-inductance of one of the stator phases is expressed by the first three terms in the Fourier series. These three coefficients primarily depend on the current and can be written as

$$L(i, \theta) = L_0(i) + L_1(i)\cos N_r \theta + L_2(i)\cos 2N_r$$

where

$$L_0 = \frac{1}{2} \left[\frac{1}{2} (L_a + L_u) + L_m \right]$$

$$L_1 = \frac{1}{2} (L_a - L_u)$$

$$L_2 = \frac{1}{2} \left[\frac{1}{2} (L_a + L_u) - L_m \right]$$

where N_r is the number of rotor poles.

$$L_a = L(\theta = 0^\circ) = \sum_{n=0}^{n=k} a_n i^n$$

L_a is the aligned position inductance as a function of phase current. Similarly, the inductance midway between the aligned and un

aligned positions as functions of phase current can be expressed as follows:

$$L_m = L\left(\theta = \frac{\pi}{2N_r}\right) = \sum_{n=0}^{n=k} b_n i^n$$

$$L_u = L\left(\theta = \frac{\pi}{N_r}\right)$$

It is worthwhile mentioning here that the inductance at the unaligned position is assumed to be independent of the phase current, which happens to be a fairly valid assumption. In addition, k is the degree of approximation.

The phase inductance expressions for the other phases are basically shifted and are similar. The coefficients a_n and b_n are determined by curve-fitting methods. This ensures that the obtained inductance profile matches the profile which would be obtained experimentally. Back EMF is expressed as

$$e = \frac{d\psi}{dt} = \frac{d\psi}{d\theta} \frac{d\theta}{dt} + \frac{d\psi}{di} \frac{di}{dt}$$

where i and θ are independent variables. Hence, the expression for back EMF can be written as follows:

$$e = \frac{d\psi}{dt} = \frac{d(Li)}{dt} = \frac{d(Li)}{d\theta} \frac{d\theta}{dt} + \frac{d(Li)}{di} \frac{di}{dt}$$

$$e = i \frac{dL}{d\theta} \omega + i \frac{dL}{di} \frac{di}{dt} + L \frac{di}{dt}$$

The expression for L is used in order to derive a solution in a closed form for the back EMF. This is written as follows:

$$e = -\frac{N_r}{2} i \omega [(L_a - L_u) \sin N_r \theta + (L_a + L_u - 2L_m) \sin 2N_r \theta]$$

$$+ \frac{di}{dt} \left\{ \frac{1}{2} \left[\frac{1}{2} (L_a^* + L_u) + L_m^* \right] + \frac{1}{2} (L_a^* - L_u) \cos N_r \theta \right.$$

$$\left. + \frac{1}{2} \left[\frac{1}{2} (L_a^* + L_u) - L_m^* \right] \cos 2N_r \theta \right\}$$

where

$$L_a^* = \sum_{n=0}^{n=k} (n+1) a_n i^n$$

$$L_m^* = \sum_{n=0}^{n=k} (n+1) b_n i^n$$

In addition to the above derived set of equations, an expression for the developed electromagnetic torque can also be derived in the closed form:

$$T = -\frac{N_r i^2}{4} [(L_a^{**} - L_u) \sin N_r \theta + (L_a^{**} + L_u - 2L_m^{**}) \sin 2N_r \theta]$$

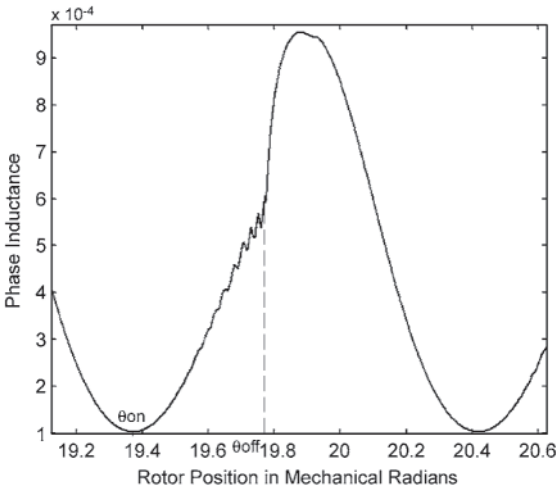


FIGURE 9.14 Phase inductance vs. rotor position from the dynamic modeling.

where

$$L_a^{**} = \sum_{n=0}^{n=k} \frac{2a_n}{n+2} i^n$$

$$L_m^{**} = \sum_{n=0}^{n=k} \frac{2b_n}{n+2} i^n$$

The mechanical equation of the drive system is given as follows:

$$T - T_L = J \frac{d\omega}{dt}$$

$$\omega = \frac{d\theta}{dt}$$

T_L is the load torque, which is generally a function of speed. Furthermore, J is the angular moment of inertia of all the rotating masses. The above equations present the dynamics of the SRM drive

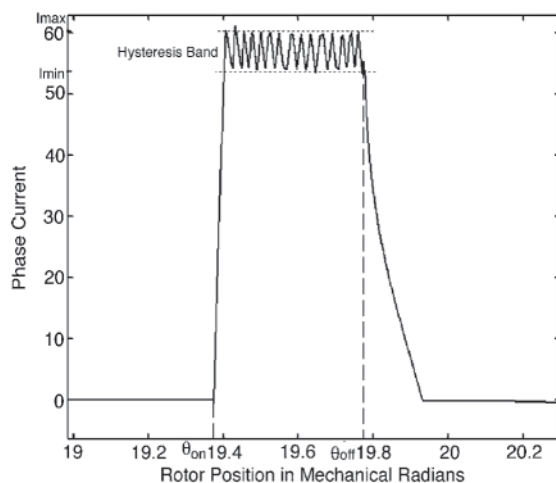


FIGURE 9.15 Phase current vs. rotor position from the dynamic modeling.

system. In addition, they also describe the terminal characteristics and the electromagnetic torque developed by one phase of the machine. As was mentioned earlier, the same applies to the other phases also, but with appropriate phase shifts and currents. It is important to note that the total electromagnetic torque developed by the motor is the sum of the instantaneous torques of the individual phases.

For a typical four-phase 8/6 SRM drive, the inductance model and phase current for phase 1 and the corresponding phase torque and radial force produced are given in Figures 9.14–9.18. These waveforms are based on the dynamic model of the SRM.

The inductance profile for all four phases of the 8/6 SRM is shown along with the phase currents, torque, and radial forces in

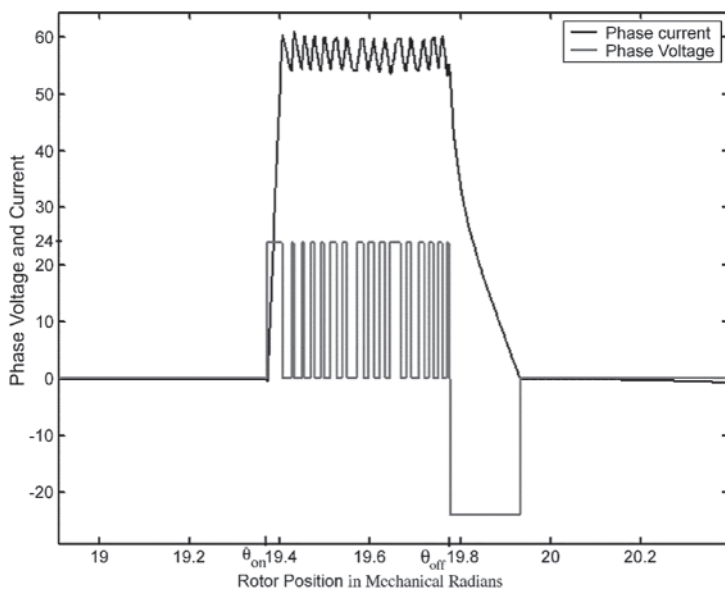


FIGURE 9.16 Phase voltage and current vs. rotor position from the dynamic modeling.

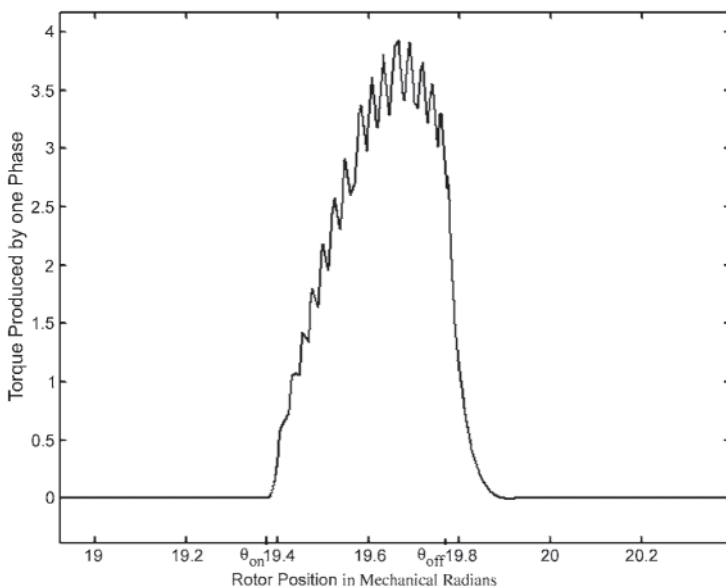


FIGURE 9.17 Torque per phase vs. rotor position from the dynamic modeling.

[Figures 9.19–9.24](#). The current overlap provides higher torque output but introduces increased torque ripples. [Figures 9.25 and 9.26](#) depict how torque varies with varying turn-on and turn-off angles.

The output torque and radial force with phase 2 under fault are shown in [Figs. 9.27 and 9.28](#), respectively. It is found that the SRM operates close to a no-fault case but with reduced performance. This is primarily due to the absence of the excitation source on the rotor and the machine windings being physically and electromagnetically isolated from one another.

The simulation results indicate that maximum torque is obtained over -30 to -7 mechanical degrees, but is decreased when turn-on and turn-off angles are moved beyond these regions. This was

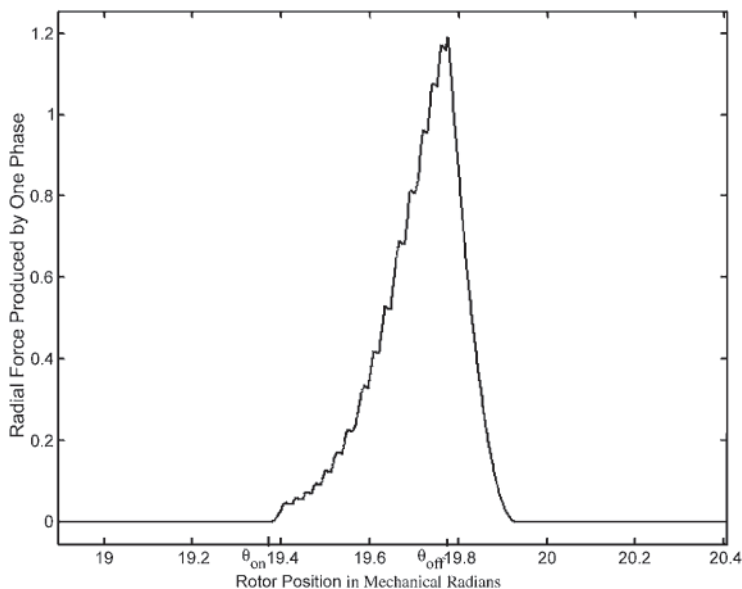


FIGURE 9.18 Radial force per phase vs. rotor position from the dynamic modeling.

also accompanied with higher torque ripples. Phase current overlapping provides the possibility of increasing the torque output by an appreciable degree without increasing the current levels, but again this brings high torque ripples and distorted radial forces. The output torque and radial force with phase 2 under fault highlight the potential of SRMs to operate reliably even under a phase fault with reduced performance.

9.5 CONTROL OF SRMs

The choice of the right control system is critical for the SRM system design. If the control strategy is defined properly, it provides a better

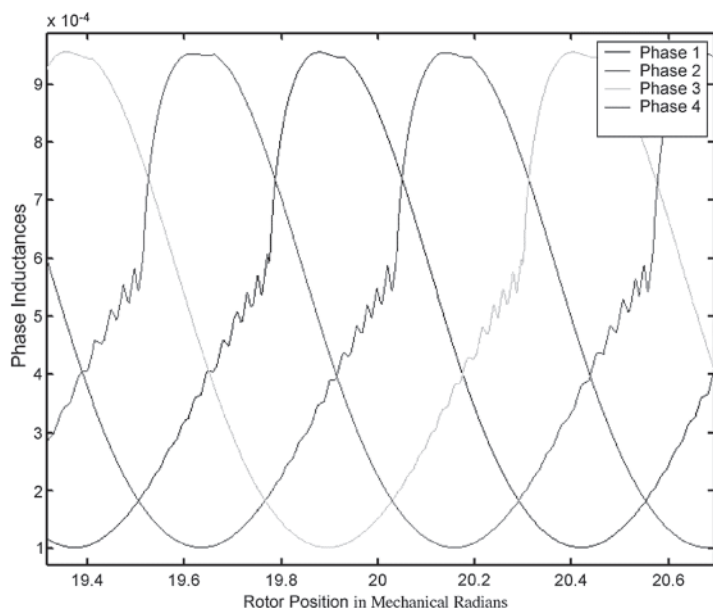


FIGURE 9.19 Phase inductance vs. rotor position from the dynamic modeling.

motor performance, lower energy usage, quieter operation, greater reliability, fewer system components, and a better dimension of the power elements.

Figure 9.29 shows phase inductance and ideal phase current and torque for the motoring and generating modes of operation. With the increase in inductance, the windings are excited for the motoring operation. The ideal waveforms of torque and current are shown in the figure for only one phase. However, by combining instantaneous values of the electromagnetic torque pluses for all phases, we can obtain total torque. It is seen that the machine produces discrete torque pulses, but by proper design of overlapping inductances we can produce continuous torque. For the motoring

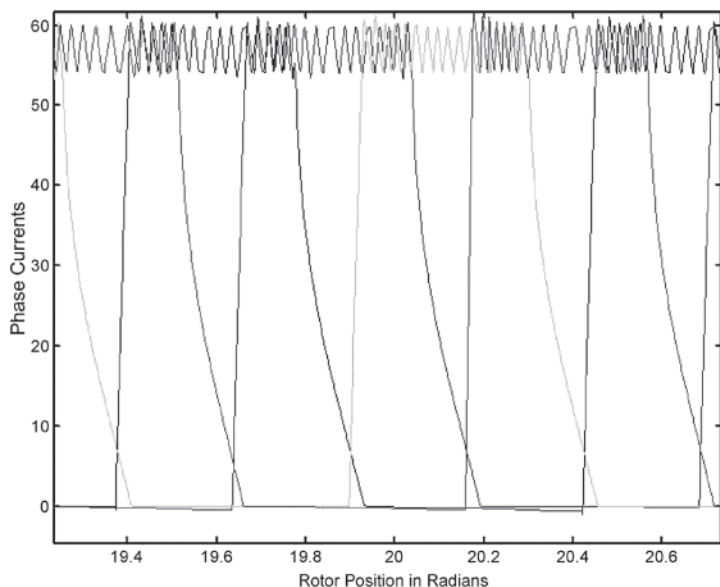


FIGURE 9.20 Phase current vs. rotor position from the dynamic modeling.

mode, in the ideal case, the current pulse is applied to the winding during the positive slope of the inductance (from the unaligned position to the aligned position). The average torque is controlled by adjusting the magnitude of the phase current or by varying the dwell angle (the angle from the turn-on instant to the turn-off instant). However, to reduce the torque ripples, it is advisable to keep the dwell angle constant and vary the magnitude of the phase current. By varying the dwell angle, we can ensure a safer operation with more control flexibility. In order to have a negative torque (generating mode), the current pulse is applied to the winding during the negative slope of the inductance (from the aligned position to the unaligned position).

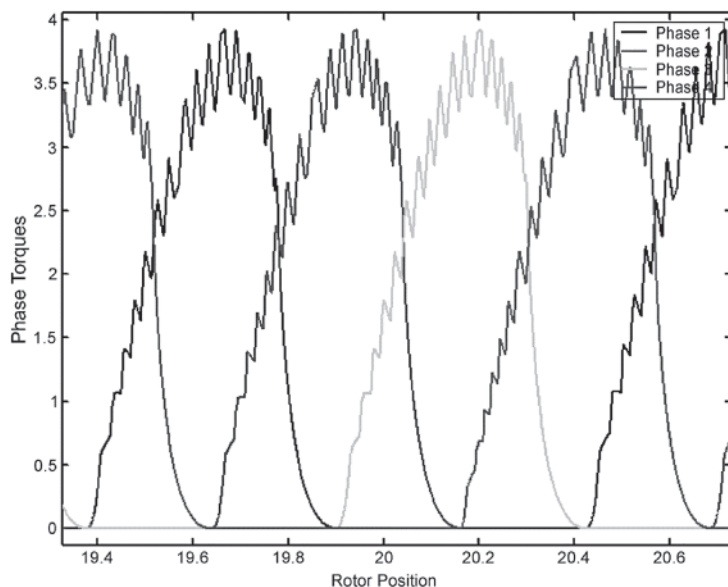


FIGURE 9.21 Phase torques vs. rotor position from the dynamic modeling.

9.5.1 Low-Speed Operation

The most popular control method for low-speed operation is the hysteresis control, or bang-bang control. This technique is also known as current control method. The switches are turned off and on according to whether the current is greater or less than the reference current. The error is used directly to control the states of switches. The phase current is limited within the preset hysteresis band. The waveforms are shown in Fig. 9.30. As the supply voltage is fixed, the switching frequency varies as the current error varies. Hence we can obtain precise current control. The tolerance band may be considered the main design parameter, but the noise filtering is difficult due to the varying switching frequency.

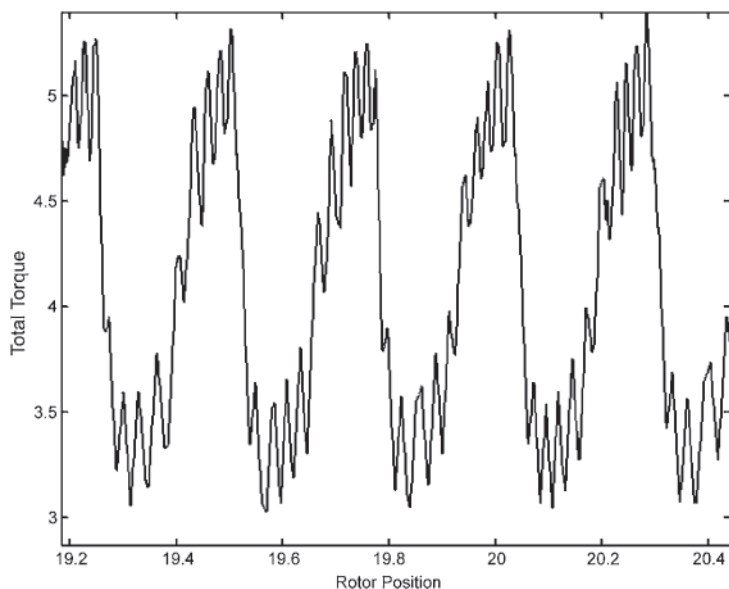


FIGURE 9.22 Torque vs. rotor position from the dynamic modeling.

Figure 9.31 shows the equivalent circuit of one phase of the classic two-switch-per-phase SRM driver. Figure 9.32 shows the equivalent circuit when the two switches are on. In this mode, the DC bus voltage is applied across the phase winding. Since the back EMF voltage is less than the DC bus voltage, the current increases. As soon as the current reaches the maximum current set by the hysteresis control, the two switches are turned off and, as a result, the two diodes conduct. Figure 9.33 shows the equivalent circuit when the two diodes are on. In this mode, the DC bus voltage is applied across the phase winding with negative polarity. Therefore, the phase current decreases. This mode continues until the phase current reaches the minimum current set by the hysteresis control (maximum current minus the hysteresis band). When the current reaches the minimum current, the two switches are turned on.

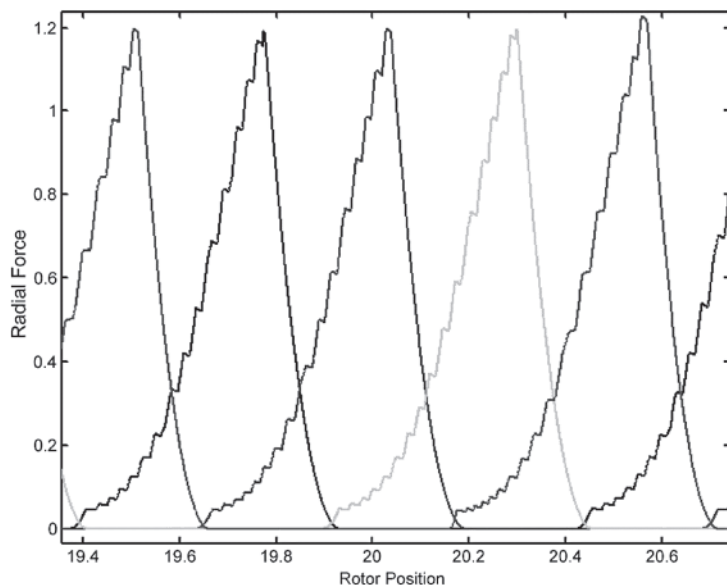


FIGURE 9.23 Radial force per phase vs. rotor position from the dynamic modeling.

Therefore, the two diodes are forced to be off. This hysteresis operation continues until the turn-off time. At the turn-off time, the two switches are turned off and the two diodes conduct. The current decreases until it reaches zero.

The technique for low-speed operation is a bipolar switching scheme because $+V_{DC}$ and $-V_{DC}$ are applied across the phase winding. Figure 9.34 shows the phase inductance, voltage, and current for the unipolar switching scheme. In this method, when the current reaches the maximum limit, instead of turning both switches off, only one of the switches is turned off. Therefore, one switch and one diode conduct and the voltage across the phase winding is zero. The current decreases, but slower than in the bipolar method. The hysteresis operation continues until the turn-off

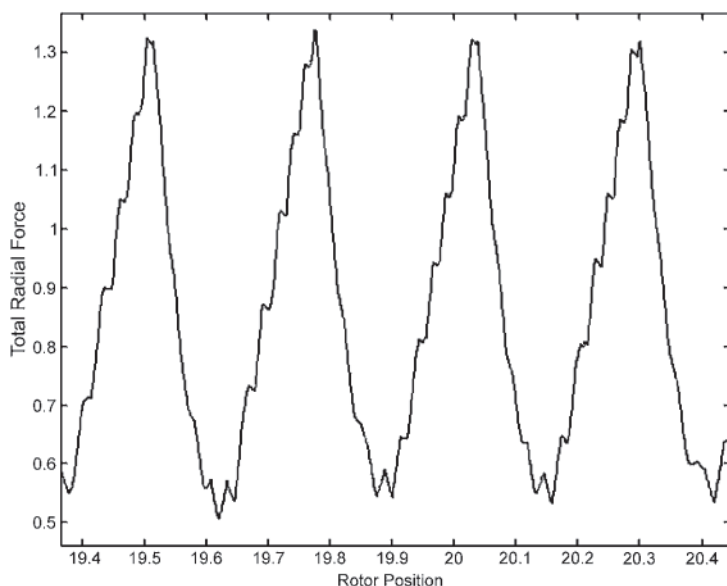


FIGURE 9.24 Radial force vs. rotor position from the dynamic modeling.

time when both switches are turned off. The two diodes conduct afterward and the voltage across the phase winding is $-V_{DC}$. The switching frequency in a unipolar switching scheme is less than the switching frequency in a bipolar switching scheme.

Bipolar and unipolar switching schemes have variable switching frequency. This is their main disadvantage. In order to have a constant switching frequency, a pulse width modulation (PWM) technique can be used. This strategy is useful in controlling currents at low speeds. Here the supply voltage is chopped at a fixed frequency with a duty cycle depending on the current error. Thus, both current and rate of change of current can be controlled. There are two main PWM techniques. In the first method, both switches are driven by the same pulsed signal, i.e., two of them are switched

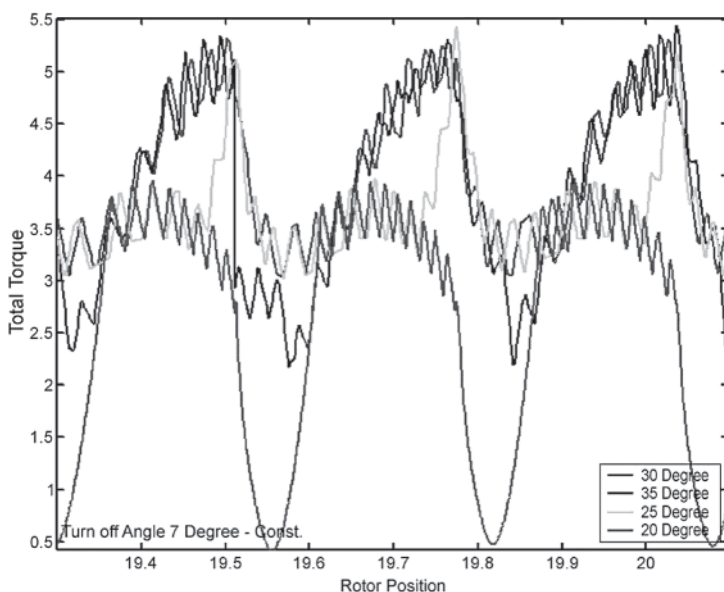


FIGURE 9.25 Torque vs. rotor position as a function of turn-on angle from the dynamic modeling.

on and off at the same time. This makes the overall design simple and cheap, but it increases current ripples. The second method is to keep the low-side switch on during the dwell angle, and the high-side switch is switched according to the pulse signals. This may help in current ripple minimization. Figure 9.35 shows the phase inductance, voltage, and current for the PWM switching technique.

9.5.2 High-Speed Operation

As the motor speed increases, it becomes difficult to regulate the current because of the combination of the back EMF effects and a reduced amount of time for the commutation control. At high

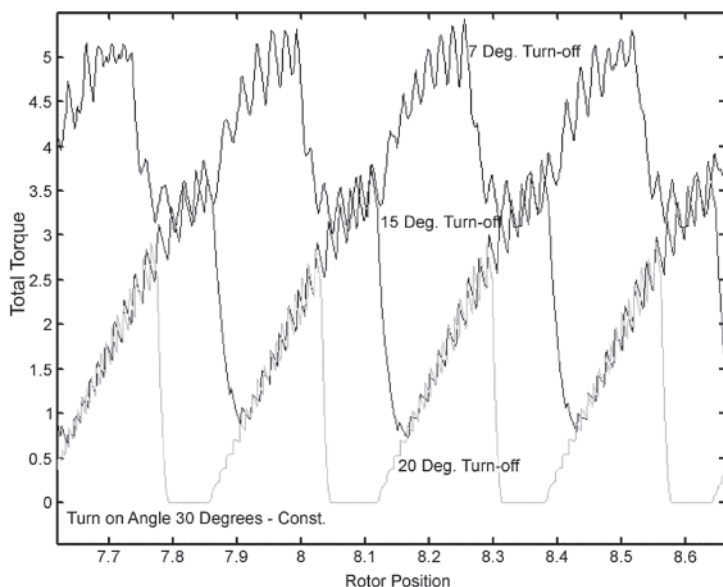


FIGURE 9.26 Torque vs. rotor position as a function of turn-off angle from the dynamic modeling.

speed, control can be obtained by increasing the conduction time (greater dwell angle), by advancing fire angles, or by controlling both. The difference between the turn-on angle and turn-off angle is known as the dwell angle.

Figure 9.36 shows the phase inductance, voltage, and current for high-speed operation. In high-speed operation, the current never reaches the hysteresis limit due to the larger back EMF. In fact, there is only one pulse for the current. Therefore, high-speed operation is also known as single-pulse operation. By adjusting the turn-on and turn-off angles so that the phase commutation begins sooner, we gain the advantage of producing current in the winding while the inductance is low and also of having additional time to reduce the

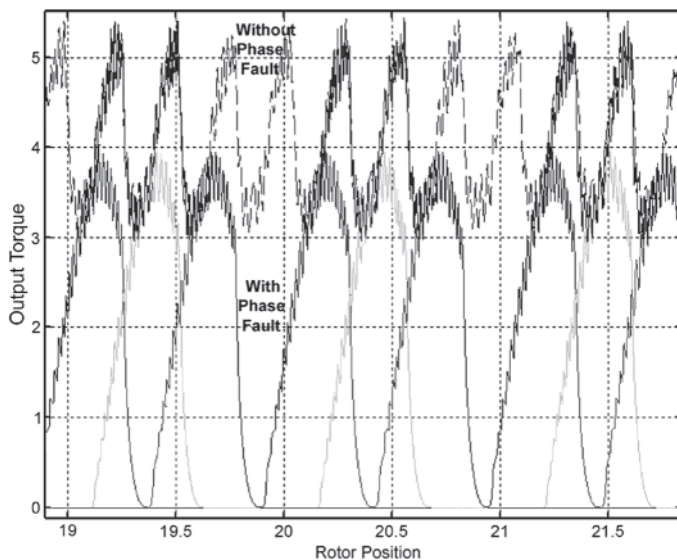


FIGURE 9.27 Output torque vs. rotor position with a fault in phase 2 from the dynamic modeling.

current in the winding before the rotor reaches the negative torque region. It should be noted that the marginal speed between the high-speed and low-speed regions is the base speed.

9.6 OTHER POWER ELECTRONIC DRIVERS

9.6.1 Miller Converter ($n + 1$ Topology)

Figure 9.37 shows the SRM driver with Miller converter. In this configuration, there is one switch for each phase. There is also one common switch for all phases. Therefore, this converter is also known as the one common switch configuration and $n + 1$ topology driver (n is the number of phases). This configuration has fewer

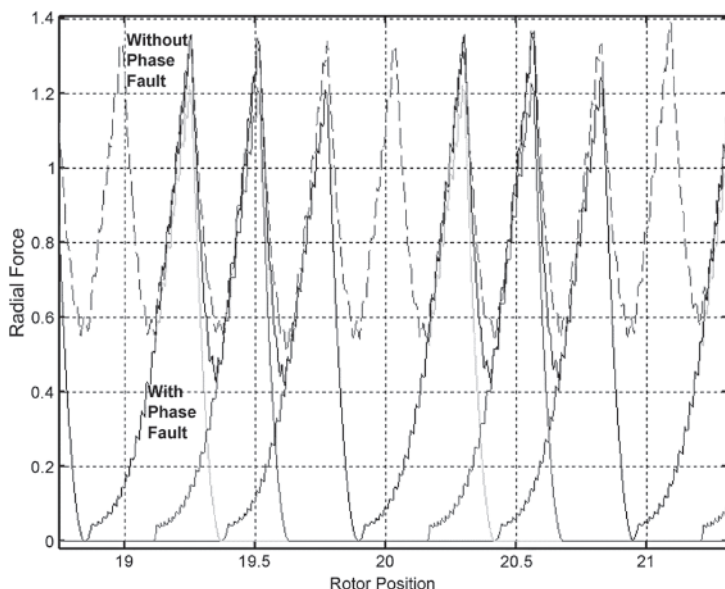


FIGURE 9.28 Radial force vs. rotor position with a fault in phase 2 from the dynamic modeling.

switches and diodes compared to the classic converter. Another advantage is that the Miller converter offers the lowest kVA inverter rating for a given drive power rating. However, the Miller converter has less flexibility. This is because the control angle range is limited since one switch is shared as the common switch. In addition, two phases of the machine cannot conduct simultaneously. Figure 9.38 shows the phase inductance, voltage, and current for a Miller converter.

A Miller converter has three modes of operation in low speed. In mode 1, as shown in Figure 9.39, S1 and S4 are turned on and D1 and D4 are off. Input DC bus voltage is applied across the phase winding. Therefore, phase current increases. Input source current is

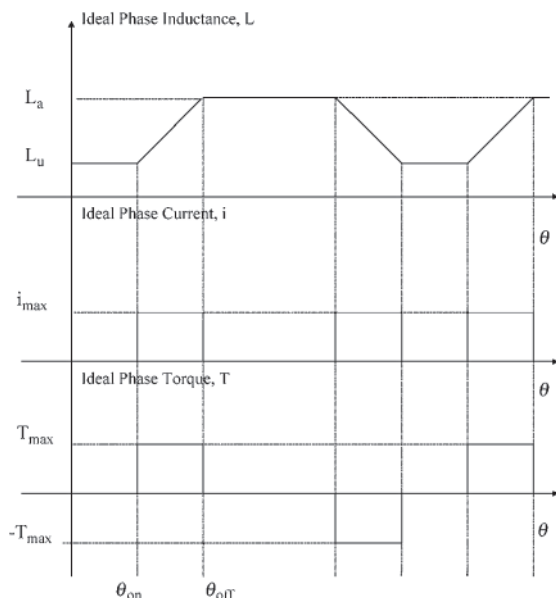


FIGURE 9.29 Phase inductance and ideal phase current and torque for motoring and generating modes of operation.

equal to the motor phase current. When the phase current reaches the maximum hysteresis current, S1 is turned off (mode 2 as shown in Figure 9.40). As a result, D4 conducts and the voltage across the phase winding is zero. In fact, this is a unipolar switching scheme. Input source current is zero. Phase current decreases until it reaches the minimum current set by the hysteresis control. Then S4 is turned on and the converter operates in mode 1. The converter switches between modes 1 and 2 until the turn-off time. At the turn-off instant, both S1 and S4 are turned off (mode 3 as shown in Figure 9.41). As a result, D1 and D4 conduct. Input DC bus voltage is applied across the phase winding with negative polarity. Therefore, phase current decreases until it reaches zero. During this mode, the input DC source is recharged.

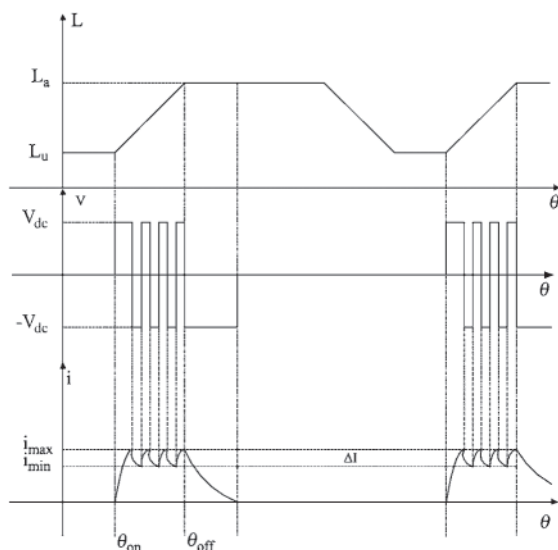


FIGURE 9.30 Phase inductance, voltage, and current for low-speed operation with hysteresis control.

9.6.2 R-Dump Converter

Figure 9.42 shows the SRM driver with an R-dump converter. In this configuration, there is only one switch for each phase without any common switch. Therefore, this is a low-cost SRM driver. However, the efficiency is low because of the dump resistor. Figure 9.43 shows the phase inductance, voltage, and current for an R-dump converter.

The R-dump converter has two modes of operation in low speed. In mode 1, as shown in Fig. 9.44, S1 is turned on. D1 is off since it is reverse biased because the capacitor voltage is applied across it with negative polarity. Input DC bus voltage is applied across the phase winding. Therefore, phase current increases. Input current is equal to the phase current. When the phase current

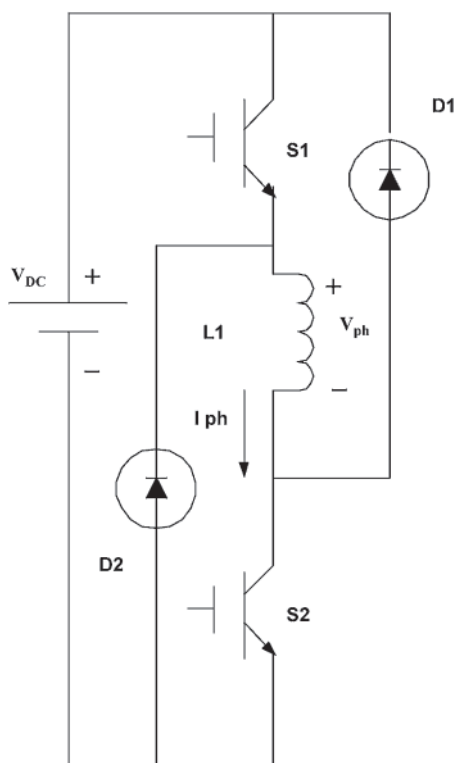


FIGURE 9.31 Equivalent circuit of one phase of a classic two-switch-per-phase SRM driver.

reaches the maximum hysteresis current, S1 is turned off (mode 2 as shown in [Figure 9.45](#)). D1 is forced to conduct. Since the capacitor voltage is greater than the DC bus voltage, a negative voltage is applied across the phase winding. Therefore, the phase current decreases. When the phase current reaches the minimum current set by the hysteresis control, mode 1 repeats. At turn-off time, the converter operates in mode 2 until the phase current reaches zero.

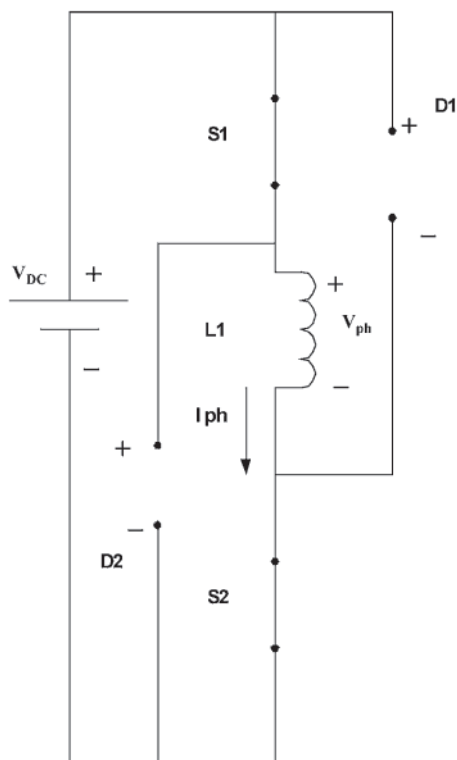


FIGURE 9.32 Equivalent circuit when the two switches are on.

Because of the resistive power loss in the dump resistor, in mode 2, efficiency of this driver is low.

9.6.3 C-Dump Converter

As shown in [Fig. 9.46](#), in order to improve efficiency, instead of using a dump resistor like the R-dump converter, a C-dump converter uses an energy dump capacitor. This configuration is a

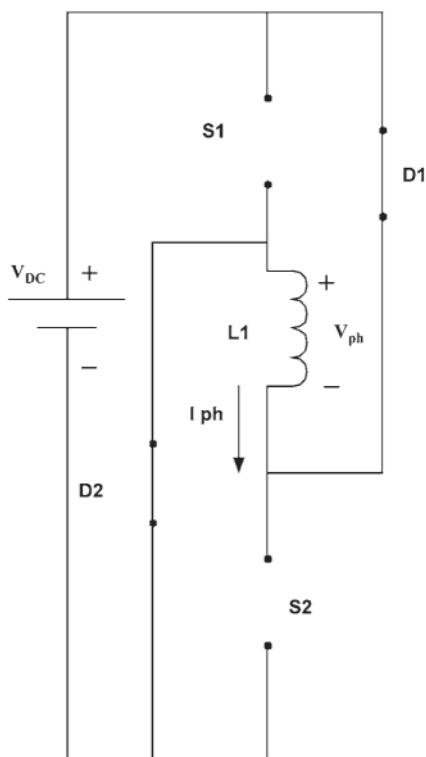


FIGURE 9.33 Equivalent circuit when the two switches are off.

single-switch-per-phase converter. Therefore, the packaging is compact. The DC source capacitor also has less ripple. In this topology, similar to the classic converter, both positive and negative DC bus voltage can be applied to the phase windings. This in turn provides control flexibility to improve the performance of the motor by reducing torque ripples and acoustic noise. However, the common switch has higher voltage and current ratings. Another disadvantage is that only motoring mode is possible. Figure 9.47 shows the phase inductance, voltage, and current for a C-dump converter.

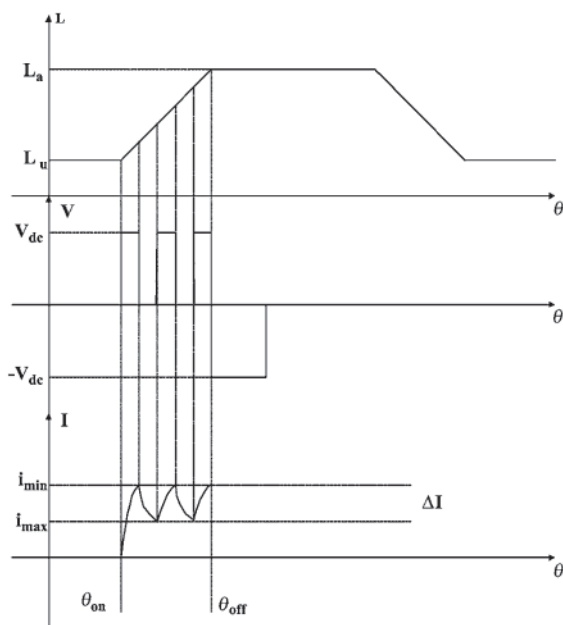


FIGURE 9.34 Phase inductance, voltage, and current for the unipolar switching.

The C-dump converter has seven operating modes. In mode 1, as shown in Figure 9.48, S1 is turned on; other switches and diodes are off. The input DC bus voltage is applied across the phase winding. Therefore, phase current increases. Input source current is equal to the phase winding current. When the phase current reaches the maximum hysteresis current, S1 is turned off. As a result, D1 is forced to conduct (mode 2, Figure 9.49). In mode 2, D4 and S4 are also off. The voltage applied across the phase winding is $-(V_c - V_{DC})$. Capacitor voltage is greater than the input DC bus voltage. The phase current decreases until it reaches the minimum hysteresis current. In mode 3, (Figure 9.50), all the switches and diodes are off. Phase voltage and current are zero.

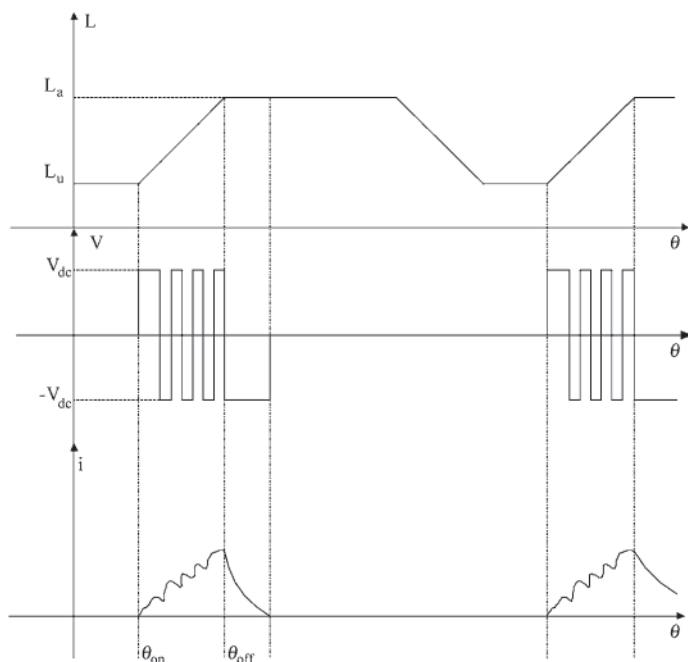


FIGURE 9.35 Phase inductance, voltage, and current for PWM switching.

In order to maintain a constant voltage across the dump capacitor, S4, D4, and L4 form a DC/DC buck converter. It is a step-down chopper if the dump capacitor and DC bus are considered input and output, respectively. It is also a step-up chopper if the DC bus and dump capacitor are considered input and output, respectively. The task of this DC/DC converter is to maintain the dump capacitor voltage. [Figure 9.51](#) shows mode 4 when S4 is turned on while S1 is conducting. [Figure 9.52](#) shows mode 5 when S4 is on while D1 is conducting. Both modes 4 and 5 can be used to charge the dump capacitor. However, common practice is to use only mode 4 for this purpose; therefore, mode 5 is not used as mode 4

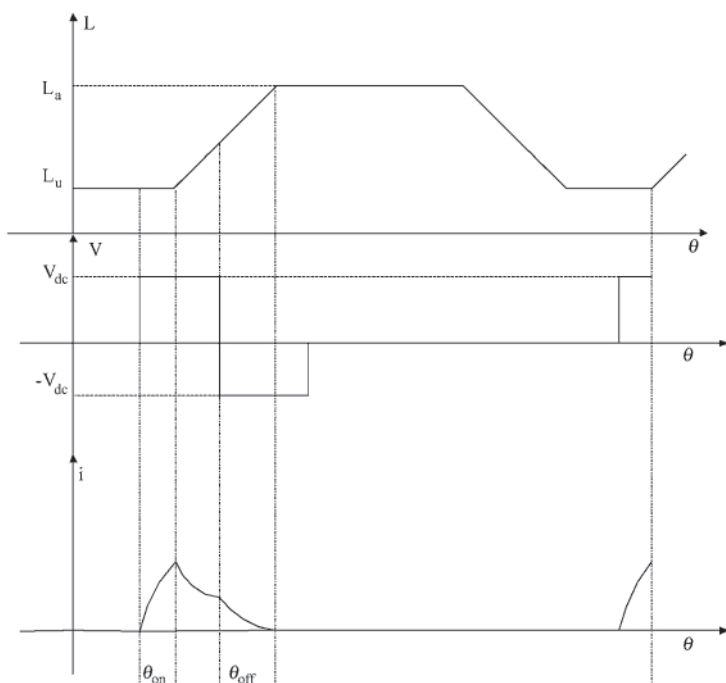


FIGURE 9.36 Phase inductance, voltage, and current for high-speed operation.

is enough to charge the dump capacitor. Simplicity is the advantage of mode 4 compared to mode 5.

In mode 6, D1 and D4 are on and S1 and S4 are off. In mode 7, S1 and D4 are on and D1 and S4 are off. In the most popular approach for the C-dump converter, only modes 1, 4, 6, and 2 are used consecutively.

9.6.4 Freewheeling C-Dump Converter

Figure 9.53 shows the SRM driver with freewheeling C-dump converter. Figure 9.54 depicts the phase inductance, voltage, and

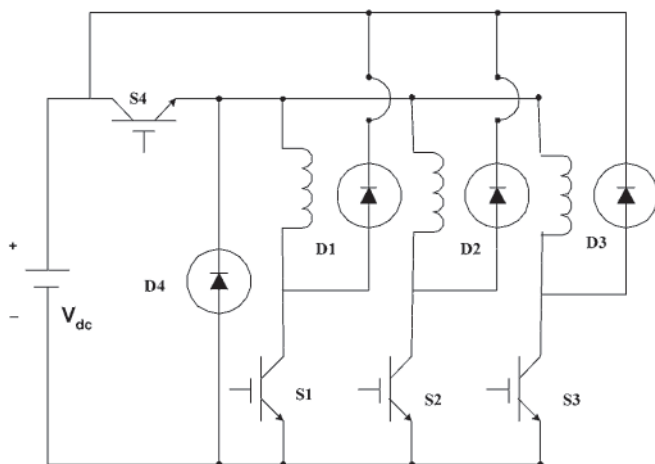


FIGURE 9.37 SRM driver with Miller converter ($n + 1$ topology).

current for this drive. This is also from the family of single-switch-per-phase converters. AC-dump converter cannot provide a zero voltage across the phase winding. Therefore, C-dump drivers always use bipolar switching schemes. However, a freewheeling C-dump converter can provide a zero voltage across the phase winding. As a result, a unipolar switching scheme as shown in Fig. 9.54 can be used. Reduced acoustic noise and torque ripples are the main advantages.

9.6.5 Split-DC Converter

Figure 9.55 shows the SRM driver with split-DC converter. Figure 9.6 depicts the phase inductance, voltage, and current for split-DC converter. In this configuration, a split-DC supply converter is used. The main disadvantage of this topology is derating the supply DC voltage. This is because only half the DC bus voltage is utilized as the applied voltage across the phase windings.

It should be noted that there are several other converter topologies for SRM drives. They include the buck-boost converter,

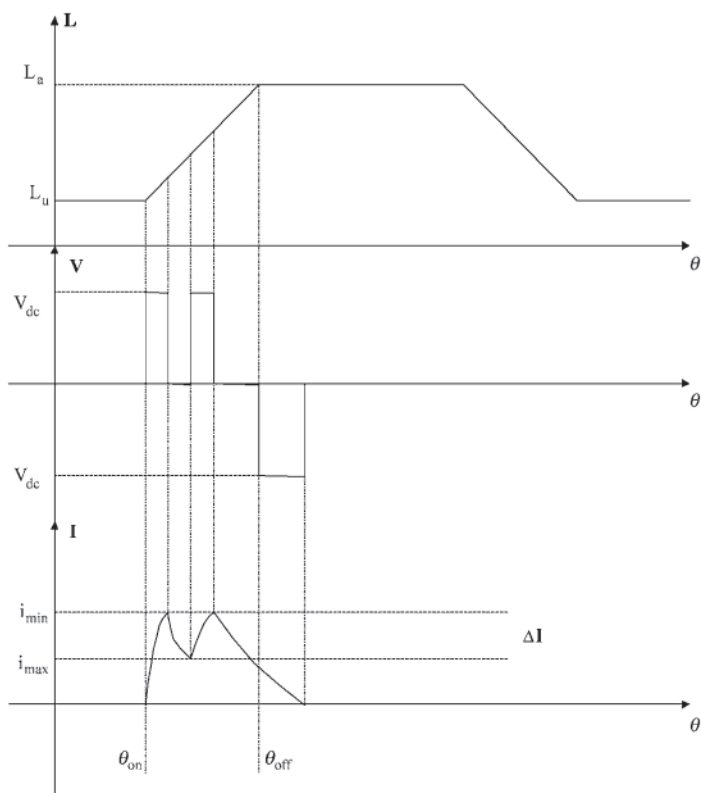
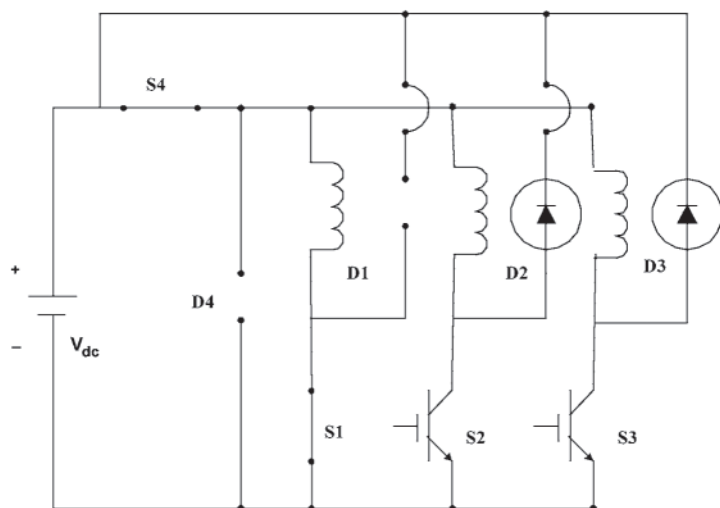
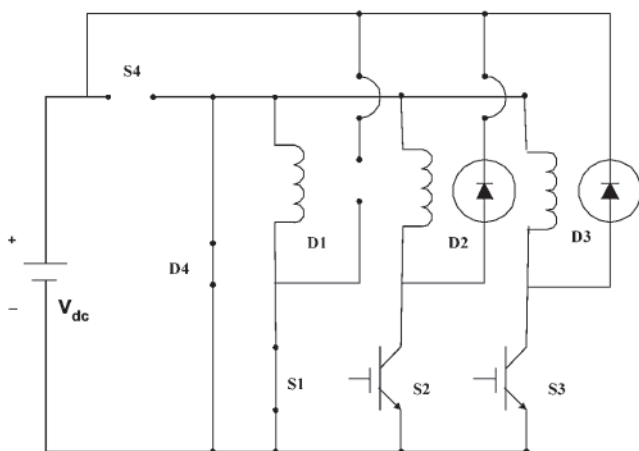


FIGURE 9.38 Phase inductance, voltage, and current for Miller converter.

FIGURE 9.39 Equivalent circuit when $S1$ and $S4$ are on.FIGURE 9.40 Equivalent circuit when $S1$ and $D4$ are on.

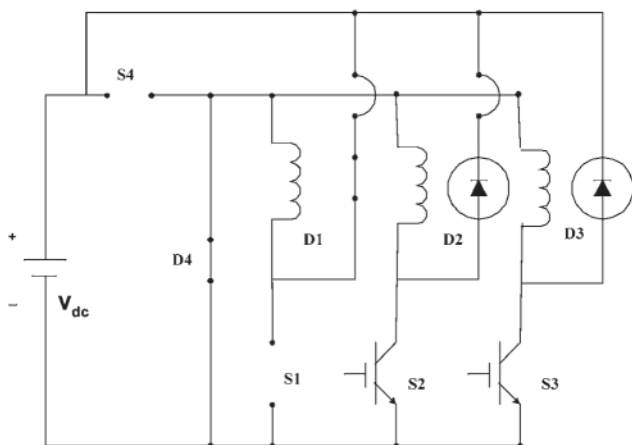


FIGURE 9.41 Equivalent circuit when D1 and D4 are on.

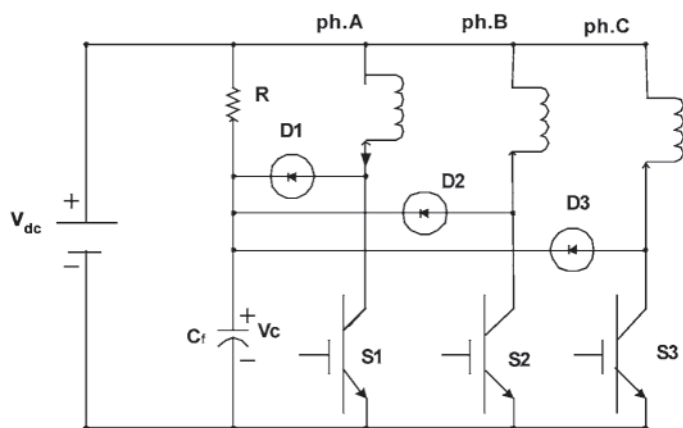


FIGURE 9.42 SRM driver with R-dump converter.

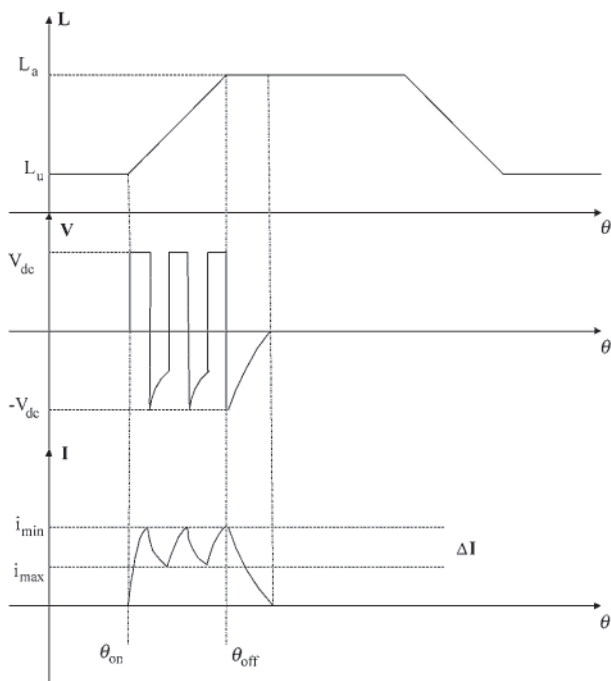


FIGURE 9.43 Phase inductance, voltage, and current for R-dump converter.

variable DC link voltage converters, the Sood converter, soft switched converters, and resonant converters.

9.7 ADVANTAGES AND DISADVANTAGES

Advantages of SRM drives are summarized as follows:

- There is saving in material cost as there is no winding or permanent magnet on the rotor.

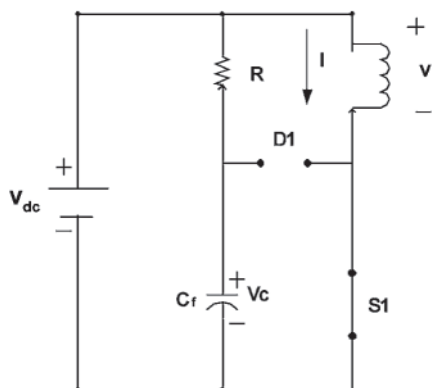


FIGURE 9.44 Equivalent circuit when $S1$ is on.

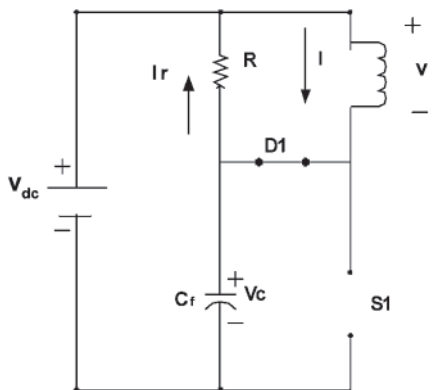


FIGURE 9.45 Equivalent circuit when $S1$ is off.

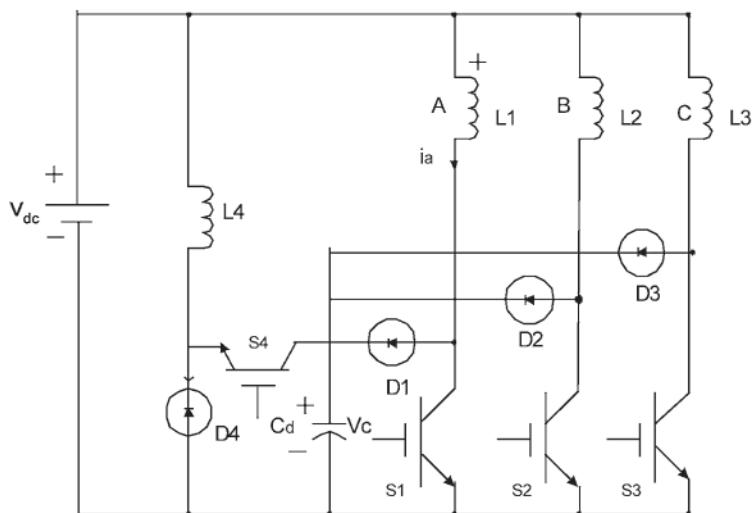


FIGURE 9.46 SRM driver with C-dump converter.

- Rotor losses are reduced due to the absence of rotor winding. The machine is therefore suited for low-voltage and current-intensive applications.
- Efficient cooling can be achieved as major losses are on the stator, which is easily accessible.
- As the size of the rotor is small, it has less moment of inertia, thus giving a large acceleration rate to the motor.
- Rotors are simple; hence, they are mechanically robust and therefore naturally suited for high-speed operation.
- The concentrated winding configuration reduces the overall cost compared to distributed windings. This configuration also reduces end turn buildup, which minimizes the inactive part of the materials, resulting in lower resistance and copper losses compared to the distributed windings in other machines.

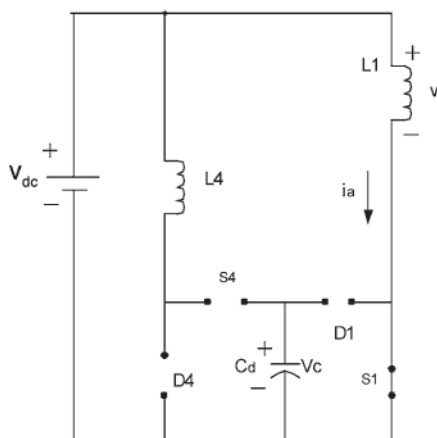


FIGURE 9.48 Equivalent circuit when $S1$ is on and other switches and diodes are off.

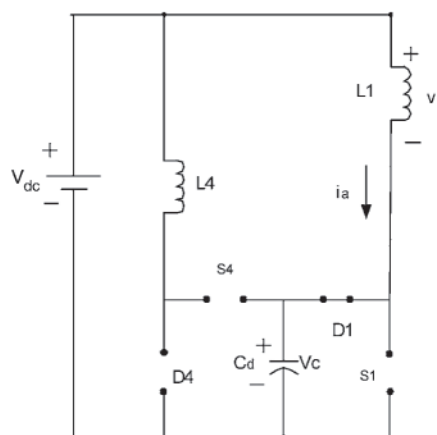


FIGURE 9.49 Equivalent circuit when $S1$ and $S4$ are off and $D1$ is on.

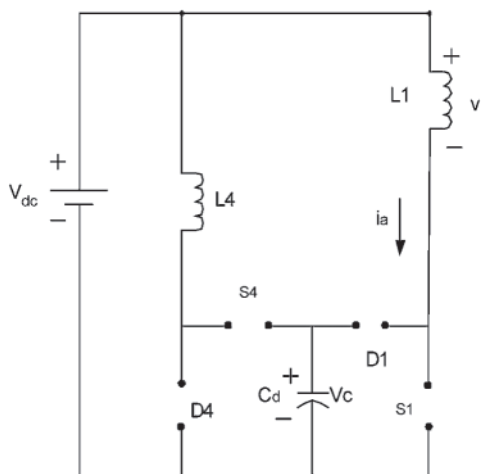


FIGURE 9.50 Equivalent circuit when all switches and diodes are off.

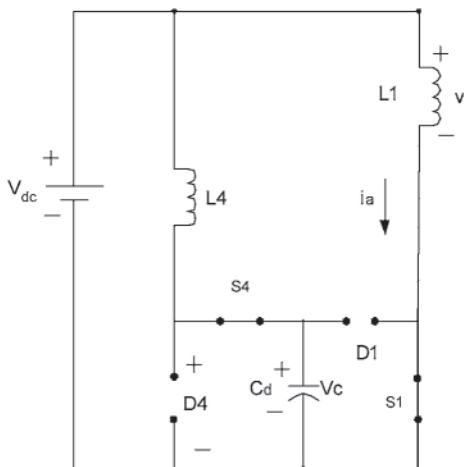


FIGURE 9.51 Equivalent circuit when S1 and S4 are on and D1 and D4 are off.

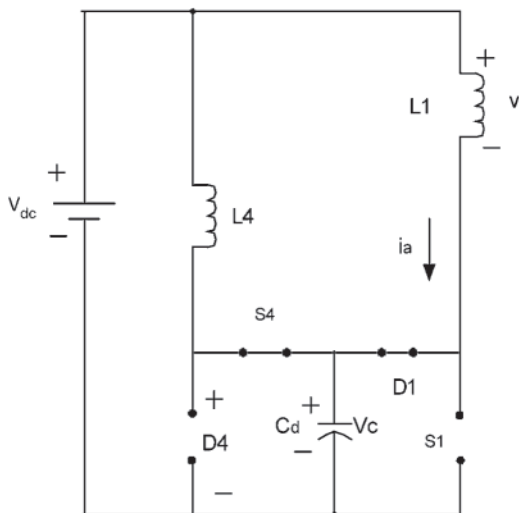


FIGURE 9.52 Equivalent circuit when D1 and S4 are on and S1 and D4 are off.

phases. As the number of phases increases, machine reliability also increases.

- They have inherent variable-speed operation.
- They provide a wide range of operating speed.
- SRMs offer great flexibility of control.
- Since power switches are in series with the phase windings and together they are parallel to the DC source voltage, there is no chance for shoot-through fault to occur; hence, higher reliability can be achieved.
- Their mechanical structure is not as stiff as, say, synchronous machines and, coupled with the flexible control system, these machines are capable of effectively absorbing transient conditions, which provides resilience to the mechanical system.
- Extended speed constant-power operation.

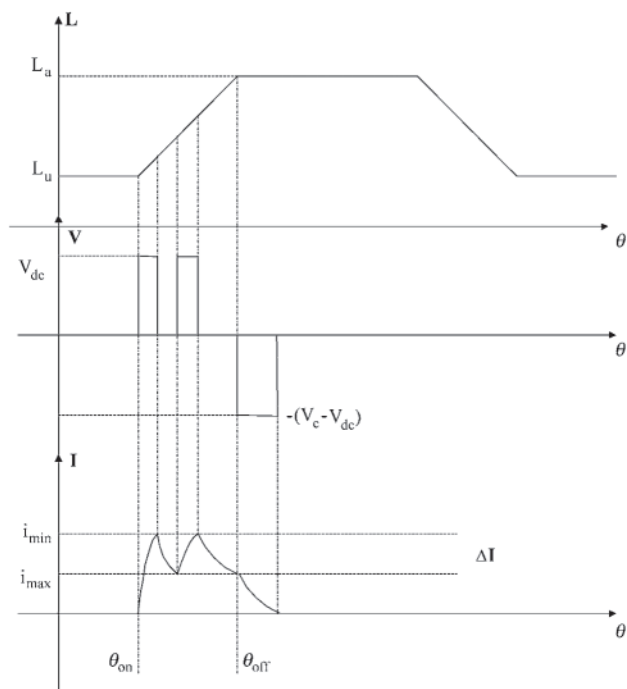


FIGURE 9.54 Phase inductance, voltage, and current for freewheeling C-dump converter.

- A separate freewheeling diode for each switch is necessary in all SRM converter topologies, which increases the overall cost compared to the H-bridge inverters.

SRM drives have many applications. Low-power applications include plotter drives, air handler motor drives, manual forklift/pallet truck motor drivers, door actuator systems, air conditioners, and home appliances such as washers, dryers, and vacuum cleaners. Medium-power applications include industrial general purpose drives, train air conditioner drives, and mining drives. High-power

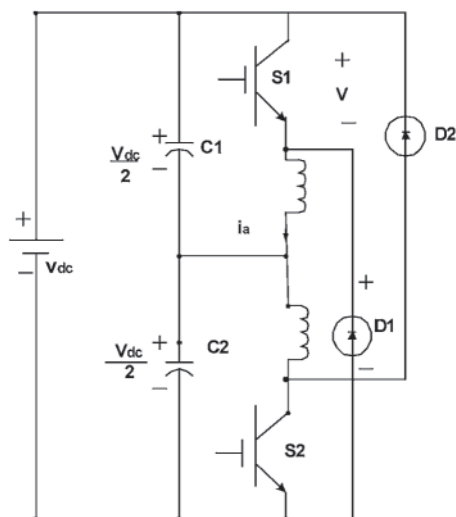


FIGURE 9.55 SRM driver with split-DC converter.

applications include electric propulsion systems, vehicular systems, domestic purpose applications like fans and pumps, and industrial adjustable-speed drives. There are also several high-speed applications such as screw rotary compressor drives, centrifuges for medical applications, and aerospace applications. Robust rotor construction and high power density are the advantages of the SRM drives for high-speed applications.

9.8 GENERATIVE MODE OF OPERATION

This is the operating mode of the switched reluctance generator (SRG) or the regenerative mode of a switched reluctance motor (SRM) when the drive is a two-quadrant or four-quadrant drive. In order to have a generating mode of operation, each phase is excited when the rotor is at the aligned position. In fact, the current pulse is provided during the negative slope of the phase inductance. [Figures](#)

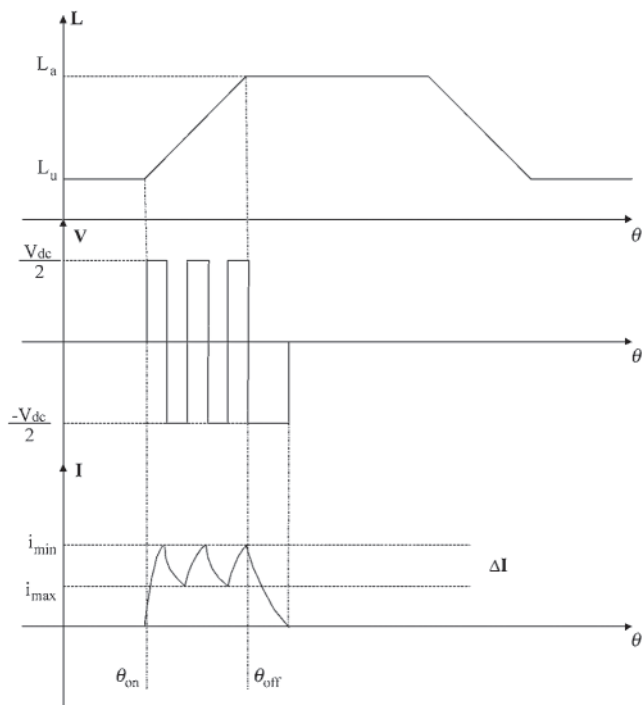


FIGURE 9.56 Phase inductance, voltage, and current for split-DC converter.

9.57 and 9.58 show the phase inductance, voltage, and current for low-speed (hysteresis or bang-bang control) and high-speed (single-pulse) operations, respectively.

The SRG has low radial vibrations as the stator phases are excited from the aligned to unaligned position; also there is absence of significant phase current. The presence of a large machine time constant also brings small radial forces. The use of antivibration configurations helps to further reduce the vibration. The radial forces being position dependent, the magnitude of the attractive forces is less and the absence of sudden changes in the rate of change

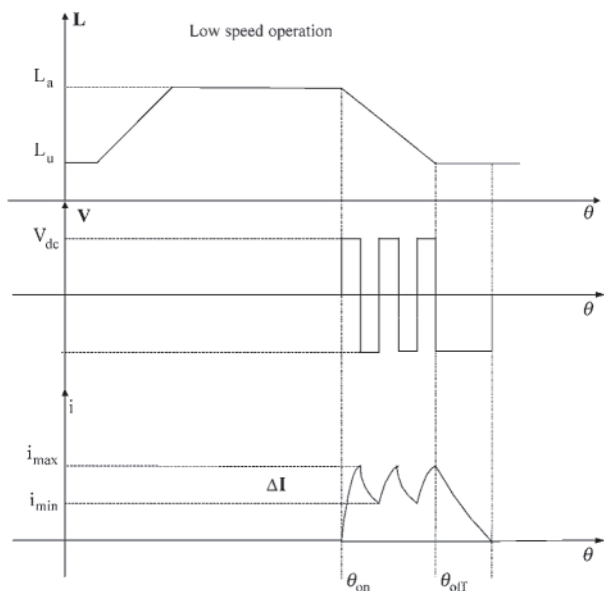


FIGURE 9.57 Phase inductance, voltage, and current for low-speed operation in generating mode.

of radial force in an SRG reduces the vibration to a large extent. Current profiling greatly reduces the noise level in an SRG, but it leads to lower performance levels.

The switched reluctance machine is unique in its operation as generator in that it does not require a permanent magnet or field windings on the rotor. The phase independence characteristic of the machine makes it extremely fault tolerant for critical applications. The absence of permanent magnets in these machines eliminates the problem of fire hazard of the machine generating into a shorted winding, compared to permanent magnet machines wherein one cannot turn off excitation. This unique feature makes the SRG a good candidate for various industrial and automotive applications.

A switched reluctance machine is operated in the generating mode by positioning phase current pulses during the periods where

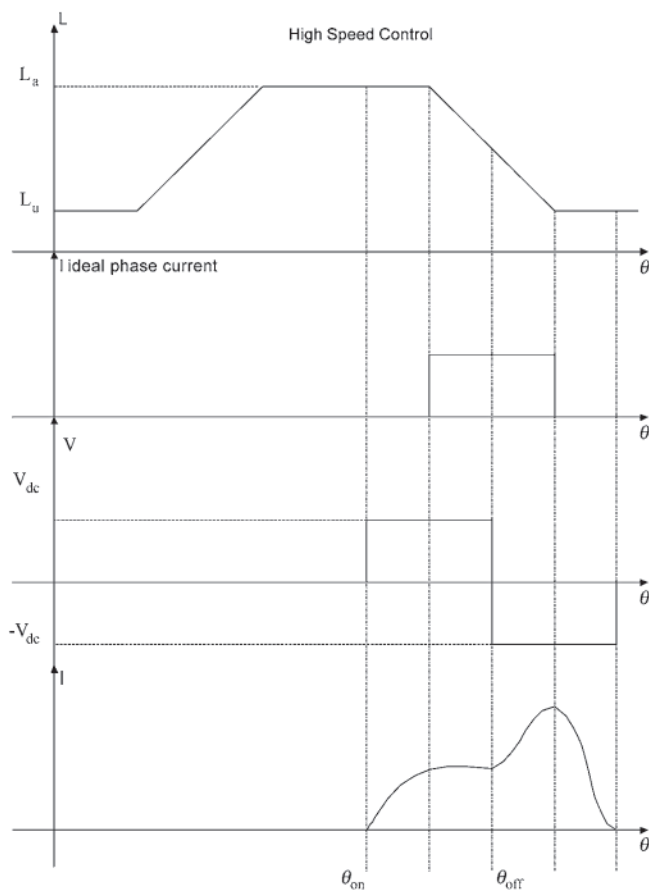


FIGURE 9.58 Phase inductance, ideal current, voltage, and current for high-speed operation in generating mode.

the rotor is positioned such that the phase inductance is decreasing. This occurs immediately after rotor and stator poles have passed alignment. Here, the machine obtains excitation from the same voltage source to which it generates power. Typically, a phase is turned on before a rotor pole aligns with that phase, drawing current from the DC source to excite the phase. Once the rotor poles pass alignment with the phase stator poles, the winding is disconnected from the DC source. It then generates into the same source with suitable connected diodes. The work done by the mechanical system to pull the rotor poles away from the stator poles is returned to the DC source. The DC source returns the excitation power plus the generated power. The control key is to position the phase current pulses to the phase stator poles in order to maximize the efficiency and to reduce the stresses on the power electronic switches. The phase current pulses during the generating mode are the mirror images of the phase current pulses in the motoring mode of operation.

An SRG is excited through a common asymmetric bridge. In a classic two-switch converter, one phase of this inverter uses the same DC source for exciting each SRG phase through two controllable switches and demagnetizing the same phase through the diodes. The conduction angle or dwell angle is the interval in which the phase is excited. Phase excitations depend on turn-on and turn-off angles. Invertors, switches, and diodes should be designed to support maximum DC source voltage and maximum phase current. Maximum voltage occurs when a switch reluctance machine operates as a generator. Main high-speed applications of SRGs are starter/alternators for automotive electrical systems and power generation in aerospace applications. The main low-speed application of SRG is for wind turbines.

9.9 ENERGY CONVERSION CYCLE

Two energy conversion cycles for an SRG at two different speeds are shown in [Fig. 9.59](#). The area enclosed by the loop corresponds to the energy converted from mechanical to electrical form for the two cases. The dot in Figure 9.59 indicates the point where the control-lable

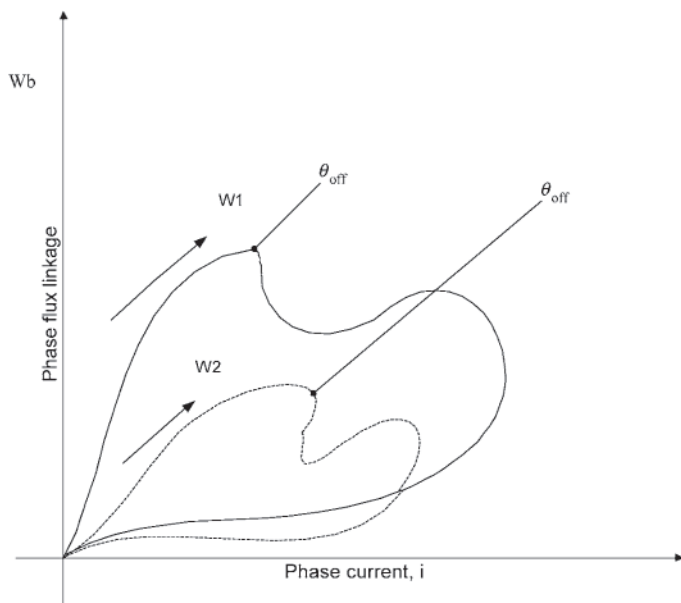


FIGURE 9.59 Energy conversion cycle.

switches are turned off and phase current is supported by diodes. Figure 9.60 gives the back EMF coefficient for the given value of the phase current. The back EMF coefficient is negative during the region of decreasing phase inductance and positive during the region of increasing phase inductance. For a certain level of the current value, the peak back EMF coefficient increases, but for any further increase in phase current, the back EMF coefficient decreases.

During excitation prior to the aligned position, phase current increases with back EMF, reducing effectiveness of the source voltage. This requires significant advancement in turn-on angle to have adequate phase current as the rotor enters the region of decreasing phase inductance. During demagnetization, phase current decreases if the source voltage is larger in magnitude than the

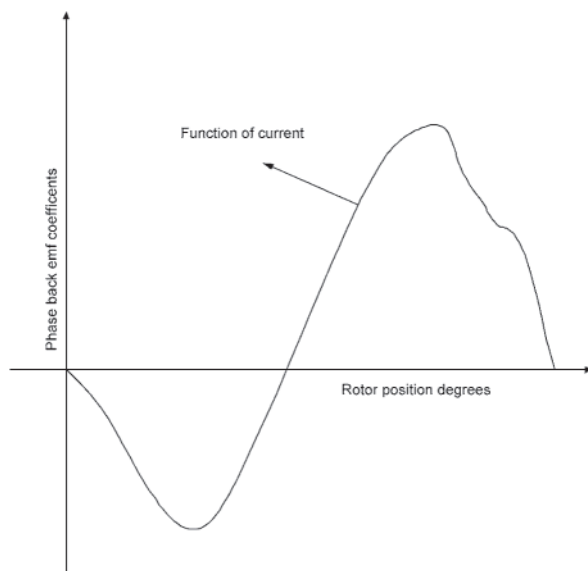


FIGURE 9.60 Phase back EMF coefficient vs. rotor position.

back EMF. At low-speed operation, multiple periods of excitations are required so that current is regulated to maintain adequate excitation as the rotor moves from the aligned position to the unaligned position. At high-speed operation, when switches are turned off, phase current increases first in the face of the negative source voltage and decreasing flux linkage.

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